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ABSTRACT

This paper describes the design strategy followed to modify a 1998 Polaris Indy Trail [1] as a part of the University of Waterloo's Team Eco-Snow's participation in the Clean Snowmobile Challenge 2000. The team's objectives are to engineer a clean, quiet snowmobile that provides recreational users with a more environmentally friendly vehicle while maintaining a snowmobile that performs on par with current production snowmobiles. The design strategy followed includes the selection of a liquid-cooled engine and subsequent modifications completed to improve the combustion process, the implementation of catalytic converters in the exhaust, and the incorporation of an improved silencer. Less innovative but somewhat overlooked strategies, such as proper carburetor tuning, are also discussed. The completed modifications are reliable and fairly inexpensive, considering the benefits provided.

INTRODUCTION

The Clean Snowmobile Challenge 2000 (CSC2000) is an engineering design competition for college and university student members of the Society of Automotive Engineers (SAE), organized and administered by the SAE, Mr. Bill Paddleford, and Dr. Lori Fussell [1].

The challenge is to modify a stock 488 cc., Polaris, Indy Trail snowmobile to improve emissions and noise while maintaining or improving its original performance characteristics. The modified snowmobile competes on March 28th, 2000, during the annual Jackson Hole World Championship Hill Climb in Jackson Hole, Wyoming. The competition events will be held in Yellowstone National Park, and Grand Teton National Park, located near Jackson Hole Resort. The competition consists of several events including emissions, noise, fuel economy, acceleration, cold start, hill climb, and design competitions. These events are spread over a three-day time period. Professional snowmobile drivers competing in the world championship will drive the modified snowmobiles during the hill-climb event [1].

The University of Waterloo's Team Eco-Snow *overall objectives* for the competition are:

1) to engineer a snowmobile that exceeds minimum emissions and noise requirements [1],
2) to engineer a snowmobile that at least maintains original performance characteristics, and
3) to win the competition.

The specific purpose of this report is to detail the approach used by Team Eco-Snow to obtain a successful entry in the Clean Snowmobile Challenge 2000.

MOTIVATION

In recent years, the increasing popularity of snowmobiles has lead to concerns about the possible environmental effects of this winter recreation [1]. For example, Yellowstone National Park (location of competition) experiences dense, cold, and often stable air-conditions. These conditions, in combination with the high emissions associated with conventional two-stroke snow machines, have the potential to produce possible unacceptable impacts to the environment.

Although snowmobiles are smaller and less numerous than the typical automobile, their emissions may add up to a significant portion of annual vehicle emissions. If a comparison is performed between a typical snowmobile and car, the hydrocarbons (HC) and carbon monoxide (CO) emissions in ppm are orders of magnitude larger for the snowmobile. Average UHC (unburned HC) emissions from snowmobiles in Yellowstone National Park are 20,759 ppm propane [1], whereas an average mid-sized car produces 161 ppm propane [2].

The competition is an attempt to bring awareness to recreational vehicle operators of the environmental impacts of their machines, as well as inspire creative talent among the competition participants in the hopes of improving snowmobile technology. As mentioned, team Eco-Snow's intention is to create an innovative, more environmentally friendly snowmobile while maintaining or improving the performance standards demanded by today's snowmobile enthusiast. It is the team's hope to develop a sound engineering solution that considers market factors as well as technical requirements.

TEAM BACKROUND

Team Eco-Snow is a student organization at the University of Waterloo. The project is managed and administered by students, under the direction and guidance of the Department of Mechanical Engineering. The team is funded by the Waterloo Engineering Endowment Fund and by industry sponsorship.

Figure 1: Team Eco-Snow

DESIGN STRATEGY

Team Eco-Snow focused on developing a strategy that would provide a successful entry for this first year of the competition, as well as completing a design that would still appeal to recreational snowmobile enthusiasts.

Design constraints and criteria relevant to the modifications outlined in this report are provided in the sections below. Many of these constraints and criteria will be restated and expanded upon when discussing the design of the individual components. A complete set of constraints and criteria is provided in the competition rules [1].

DESIGN CONSTRAINTS [1]

- Modifications to the engine, including substitution of a different engine are allowed. Both two-stroke and four-stroke engines are allowed. Engine displacement is limited to 500 cc or less for two-stroke engines, 800 cc or less for four-stroke engines.
- The snowmobile engine, or auxiliary power unit if a hybrid electric snowmobile is proposed, must run on gasoline or a blend of 10% ethanol and 90% gasoline.
- Fuel additives (with the exception of commercial two-stroke oil) are not permitted.
- The selected engine must be mountable and fit within the snowmobile body without unreasonable modifications.
- The snowmobile must be propelled with a variable ratio belt transmission.
- The modified snowmobile must also meet all applicable federal and provincial safety regulations.

DESIGN CRITERIA [1]

The design criteria listed below are the performance standards proposed by the organizers that must be achieved by Team Eco-Snow.

- Carbon monoxide emissions should be reduced by a minimum of 25% and UHC emissions should be reduced by a minimum of 50%.
- The snowmobiles may be fueled by gasoline, oxygenated gasoline (10% ethanol), or electricity (hybrid-electric).
- Snowmobile power should be maintained or improved.
- Noise will be measured during the acceleration run (full throttle) and must not exceed 74dBA, 50 feet from the road.

The team's first major decision was to continue to use a two-stroke engine because of an embedded consumer preference for the performance characteristics that a two-stroke engine provides snowmobile riders. In addition this decision provides the team with a solid platform for the competition's performance events. The team strategy then focused on modifications that would maximize competition points in the emissions, noise and fuel economy categories. Safety was also given top priority throughout the entire design process. Reliability established an additional important constraint.

The team's specific design priorities are, in summary (ordered from highest to lowest priority), as follows:

1. Use of a two-stroke engine
2. Reduction of exhaust emissions
3. Reduction of noise
4. Improvement of fuel economy
5. Maintain or improve handling and engine performance

MODIFICATIONS / CONVERSIONS

BASELINE TESTING / PERFORMANCE

The design criteria as detailed by the competition rules stated that the performance characteristics of the snowmobile should be maintained or improved. The first step in ensuring that Team Eco-Snow met this criterion was to determine a performance baseline. The unmodified snowmobile was placed on a track dynamometer [3]. The dynamometer measures the developed horsepower (seen at the track) against rpm. Results are charted over a fourteen-second interval. The maximum horsepower results are summarized in Table 1.

	Run #1	Run #2
SAE Horsepower (Max)	25.4 hp	23.6 hp
Engine Rpm (at max hp)	7424.1 rpm	7390.8 rpm
Elapsed Time (at max hp)	9.4 s	10.3 s

Table 1: Dynamometer Results

The estimated stock engine (as opposed to track) horsepower of the 488cc fan-cooled engine is approximated at 58 hp based on similar fan-cooled engines [4]. The difference in these values indicates significant losses between the engine output and the track. These values provide baseline comparisons for future testing. From this data, the effects (either positive or negative) of the engine modifications can be determined.

BASELINE EMISSIONS

The competition organizers provided baseline values for unburned hydrocarbons and carbon monoxide emissions. Emissions from the average snowmobile in Yellowstone National Park are 103,081ppm of carbon monoxide and 20,759ppm of unburned hydrocarbons as compared to propane [1]. These average emission levels were measured at approximately 7,000 above sea level and –10 to 30 degrees Fahrenheit with an infrared heat beam [1]. These average values resulted from measurements taken during two different modes of operation:

1) A gentle acceleration from a standing start to 15 mph (simulating a snowmobile pulling away from a park entrance gate) [1].

2) A climb up a gentle hill (3 to 4 percent grade) at a constant speed of 20 mph [1].

Throughout the project it was important to monitor how modifications affected the resulting emission levels. A test procedure was developed to allow quick emission measurements to be made on the spot. The procedure consists of raising the track off the ground using a test stand, running the snowmobile through a dictated procedure, and measuring emission levels using a 5-gas analyzer. During the spot test procedure development, day to day changes such as ambient air temperatures, humidity and pressure were found to play a factor, therefore, the team utilized the spot test results only to provide a general indication of the benefit or detriment of the modification. Figure 2 shows a comparison of hydrocarbon emissions against time for regular unleaded gasoline and gasoline with 10% ethanol. The graph shows a significant reduction when the 10% ethanol is used. The test represented was completed at an approximate elevation of 1000ft and a temperature of 50-60 degrees Fahrenheit.

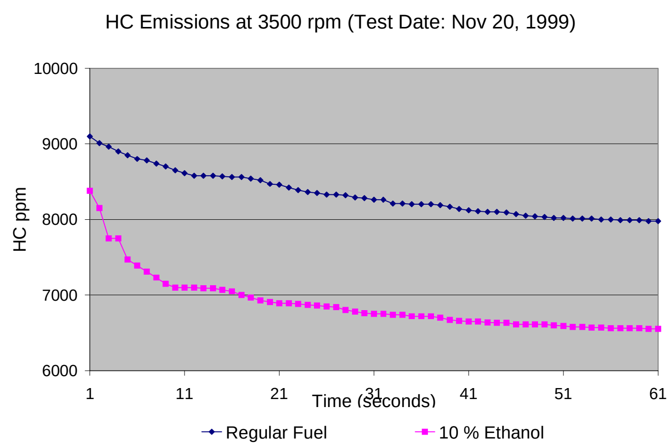

Figure 2: HC Emission Data for Regular Gasoline and Gasoline with the addition of 10% Ethanol

ENGINE SELECTION

Engine selection plays a pivotal role in determining the subsequent strategies used to reduce engine emissions. Team Eco-Snow selected a two-stroke engine, however, a four-stroke solution was examined and does hold certain advantages over a two-stroke. The following three sections examine the benefits of a four-stroke, the reasoning behind remaining with a two-stroke, the problems with two-strokes, and the methodology utilized to reduce emissions from the selected engine.

<u>Advantages and Disadvantages of a Four-Stroke</u>

Four-stroke engines are commonplace in the automobile industry and in other recreational vehicles such as motorcycles. Significant research by automobile manufactures has been completed over the years to reduce the emission levels and improve power characteristics of automobiles. Utilizing a four-stroke engine and adopting some common industry emission strategies would provide Team Eco-Snow with a detailed design methodology. These factors provide a strong incentive for the team to seriously consider using a four-stroke engine.

The design constraints allow for the use of an 800cc four-stroke or 500cc two-stroke engine. The larger allowable size of the four-stoke engine is an attempt to even the playing field in terms of achievable power. Even though similar power could be achieved with the larger four-stroke engine, a considerable amount of weight would be added to the machine. Figure 3 is a visual representation of the difference in size and weight between comparable (in terms of output) four-stroke and two-stroke engines.

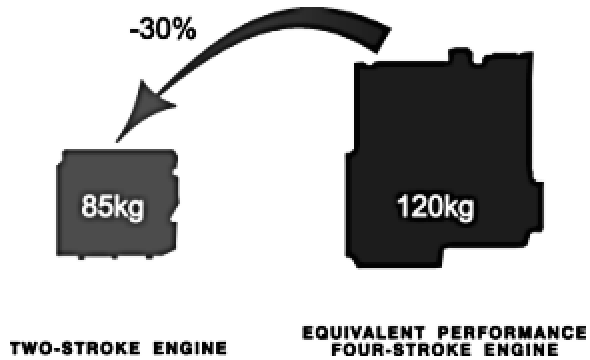

Figure 3: Two-Stroke vs. Equivalent Four-Stroke [5]

Two of the competition events require a professional snowmobile racer to drive the modified snowmobile. In the first event the racer judges the handling of the machine and in the other the racer competes in a hill-climb. In each of these events a heavier machine would be detrimental to awarded points.

Other negative aspects to a four-stroke include the need to modify the transmission. A typical four-stroke engine has a manual transmission. The driver uses a clutch and changes the gears manually. Snowmobile engines have variable ratio belt transmissions. Since the design constraints of the competition limited the drive train to a variable ratio belt transmission, major modifications would be required to convert a four-stroke's typical drive train.

The concrete emission benefits obtainable from the conversion to a four-stroke engine almost succeeded in convincing the team to select a four-stroke engine. However, because of the required modifications to install the engine, the increased weight and the resulting loss of handling and performance it was decided that this option should be dismissed but possibly considered for future competitions.

<u>Problems with Two-Stroke's</u>

Two-stroke spark-ignited engines have been adopted as the power unit for snowmobiles, motorcycles, personal watercraft and some automobiles due to their high specific power, simple construction, light weight and low production cost. Because of its unique scavenging principle, compared to the four-stroke engine, the carburetted two-stroke engine has inherent disadvantages, such as high hydrocarbon emissions, high fuel consumption and poor idle/light load combustion quality. Using fresh, fuel-rich intake air to clean or scavenge the cylinder of its exhaust gases causes these problems. The oil that is mixed with the air/fuel mixture (intended to lubricate the crankshaft) compounds this. This oil gets burnt in the combustion process significantly adding to high HC and CO emission levels as well as high levels of emitted particulate matter.

Under all loading conditions, 20 to 40% of the unburnt air/fuel mixture escapes from the exhaust port. A tuned exhaust system tries to prevent a lot of this charge from escaping the cylinder by using back pressure. A returning pressure wave, created by the shape and size of the exhaust, pushes the fresh charge of air and fuel back into the combustion chamber to be burnt. This pressure wave changes with different temperatures and different loads, and as a result, the pressure wave action is only fully realized for a very limited range of engine loading. As well, even during these optimum loading conditions some fresh charge still manages to escape into the exhaust. This escape of air/fuel into the exhaust represents a large portion of the unburned hydrocarbons present in the emissions [5].

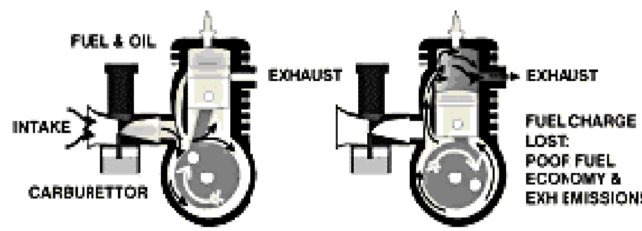

Figure 4: Loss of Fresh Fuel, Air & Oil Into [5]

The solution to the problems of a two-stroke engine seems obvious, why not just pump pure air through the engine, and inject the fuel only after all the ports have closed. This forms the basic idea of direct fuel injection (DFI). Team Eco-Snow considered implementing a direct fuel injection system but abandoned the idea due to the complexity of developing such a sophisticated system in the eight-month time frame available before the competition.

<u>Liquid-Cooling</u>

One of the most straightforward methods to reduce emissions is to burn a slightly lean air-fuel mixture (stoichiometric air/fuel ratio is 14.7, equivalent Lambda equals 1.0) and then treat the exhaust using a catalyst. Slightly lean air/fuel mixtures result in higher gas mileage, lower exhaust emissions, reduced engine power, higher engine temperatures and a slight tendency to knock or ping. Figure 5 shows how emissions can change as a result of lean or rich air/fuel mixtures.

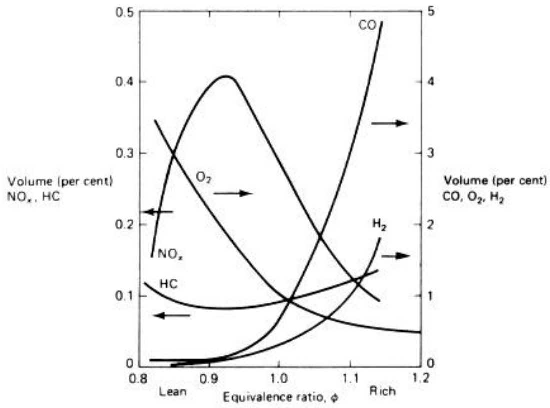

Figure 5: Effect Of Air/Fuel Ratio On Emissions [6]

Improved cooling of the combustion chamber can reduce the operating temperatures and alleviate knocking or pinging problems. The most effective method of improving the heat transfer in a two-stroke engine is to employ liquid cooling.

Team Eco-Snow decided to replace the fan-cooled engine that came with the donated snowmobile with a similar liquid-cooled version. A liquid-cooled engine provides the team with the ability to tune the engine to run leaner than the equivalent fan-cooled engine, thereby improving the fuel economy and the emission characteristics of the machine – two important criteria of the competition.

As mentioned above, using a lean air/fuel mixture would also reduce engine power. This is a concern, as one of the criteria is to improve or maintain the power characteristics of the original snowmobile. However, a comparison of snowmobiles with identical engine displacements and different cooling systems revealed that liquid-cooled engines often ran with twice the horsepower as their equivalent fan-cooled counterparts. This phenomenon is found to hold true even when comparing identical models of the same year with the only difference being the method of cooling [4].

A 2000 model Polaris liquid-cooled 500cc engine (with variable exhaust valves) was purchased. Power output of the new engine is estimated at approximately 100hp [4]. This increased horsepower provides Team Eco-Snow with room to improve emissions at the expense of a horsepower reduction, while still maintaining or improving the horsepower as compared to the original engine.

The next section details the modifications made to the new engine to improve the combustion process and reduce emissions from the source before treatment of the exhaust. From this point forward, any engine discussion will be in reference to the purchased liquid-cooled engine, unless otherwise stated.

ENGINE MODIFICATIONS

Inertia Dynamometer

In order to improve the combustion process and reduce engine emissions the team worked with a snowmobile and motorcycle shop [7] that specializes in improving the performance characteristics of their customer's machines. A fairly sophisticated "superflow" inertia dynamometer provided important engine performance data both before and after modifications. Although intended as a motorcycle dynamometer, modifications accommodated the snowmobile engine. A picture of the test set-up designed by both Team Eco-Snow and the shop owner is shown in Figure 6.

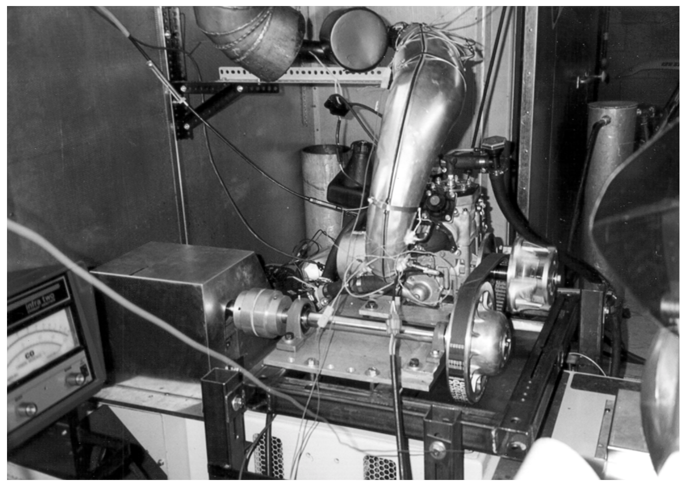

Figure 6: Inertia Dynamometer Test Set-up

Engine data such as torque and horsepower, coolant temperature, pipe temperature, static pipe pressure, and air/fuel ratio provides important performance information of the engine before and after modifications. Important data is discussed in the following sections where appropriate.

Modifications

Several engine modifications, including a change in the compression ratio, squish clearance and velocity, exhaust valve seating and exhaust valve timing were completed. A computer program gives theoretical values for important variables. An iterative procedure allowed the team to decide the best combination of all these values for an optimal engine design [8]. Figure 7 shows the engine data before the modifications, Figure A-1 contains a similar picture of the final engine data. Table 2 shows a comparison of the original engine data and the engine data corresponding to the team's design.

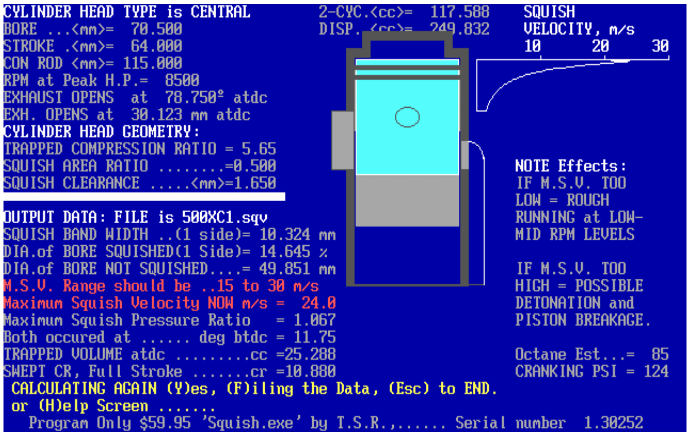

Figure 7: Unmodified Engine Values Calculated by Squish.exe [8]

	"As-Received" Condition	Design Targets
Compression Ratio	5.65	7.15
Squish Clearance	1.65 mm	1.20 mm
MSV (Mean Squish Velocity)	24 m/s	29 m/s
Exhaust Opens at:	30.123mm after top dead center	31.134mm after top dead center

Table 2: Comparison of the Original Engine Data and the Data Corresponding to the Team's Design

Compression Ratio

One of the best ways to increase the efficiency of any internal combustion engine is to raise the compression ratio. This is a very critical modification and should only be performed when it is known that operating conditions will not produce detonation and damage the engine. As seen in Table 2 the trapped compression ratio of the engine in the as-received condition is 5.65.

Standard atmospheric pressure is 29.92 in-Hg. Calculations revealed that at 7000ft there would be approximately a 20% loss in barometric pressure. These calculations were confirmed by contacting the airport at Jackson Hole. Their measurements indicated that the average uncorrected barometric pressure was approximately 24 in-Hg. If the engine remained unmodified, the pressure within the cylinder would also have dropped by 20%. This would severely reduce the efficiency and power of the engine.

By increasing the trapped compression ratio the drop in cylinder pressure can be corrected for. To maintain a similar pressure at the competition altitude a trapped compression ratio of 6.78 was required. However, since a relative increase in efficiency and performance is desired, an increase in the trapped compression ratio above 6.78 was the target. Milling material from the cylinder head and the base of the cylinder increased the trapped compression ratio. The modifications were made aiming for a calculated trapped compression ratio of 7.00 and resulted in a ratio of 7.15, which was acceptable.

Since the increase in trapped compression ratio was specifically designed for the increased elevation that would be experienced at the competition, precautions were taken at Waterloo's elevation of 1000ft so as not to damage the engine. Fuel with an octane rating of 98 was used while tuning and testing the engine.

Changes in the exhaust port timing (discussed later in the report) also required that material be removed from the cylinder base. This change affects the total volume of the cylinder and must be considered when removing material from the head.

Squish Clearance and Velocity

Squish clearance refers to the narrowest distance between the piston and the head. Most two-cycle engines utilize squish bands in their head's combustion chamber to improve the combustion process. A squish band is the flat ring commonly found around the outside edge of the combustion chamber. The squish band (in combination with the piston) causes a squeezing action on the air/fuel mixture in the combustion chamber.

As the piston moves towards top dead center (TDC) in the cylinder, the air/fuel mixture between the piston and the squish band is compressed into the center of the combustion chamber. It is this squishing action that allows the combustion process to occur faster than without the squish action. The squish action promotes air/fuel mixture turbulence, causing a more uniform mixture of the air/fuel and more complete combustion. Squish action also attempts to squeeze the air/fuel mixture around the edges of the piston, which does not get burned, towards the center of the cylinder. The increased combustion of the air/fuel results in higher combustion pressures, less compression work and more expansion work.

While squish is very beneficial, more is not always better. Too much squish action causes extreme turbulence and heating before and/or during combustion leading to detonation.

Mean Squish Velocity (MSV) is the industry standard for measuring the squish action and correctly limiting its effect. The numbers can safely vary from 0 to 30 m/s with average values in the 15 to 25 m/s. Squish velocity increases with an increase in rpm. Therefore by having a very high squish velocity at the peak rpm of the engine (approx. 8500rpm) a relatively high squish velocity will occur throughout the rpm range promoting more turbulence at lower rpm's where it has its most effect in assisting the combustion process.

The squish clearance was measured on the liquid-cooled engine and modified to increase the MSV. The original MSV was calculated to be 24m/s at 8500rpm and was changed to 29m/s at 8500rpm. These modifications were completed at the same time the milling of the head, as milling the head requires re-milling the squish band.

Snowmobile engines are designed to run at very high rpm values. When the engine was initially run on the inertia dynamometer it ran observably poor at low rpm values. Fuel was not properly mixing with the air and misfires occurred. After modifications, the engine ran perceptibly smoother with no misfiring.

Exhaust Port Timing

The relative position of the exhaust port was changed from 30.123mm after top dead center to 31.134mm after top dead center. This was completed by shaving 1mm from the base of the cylinder casing moving the relative position of the exhaust port down from the unchanged top dead center position of the crank-arm.

The relative positions of all of the transfer ports and exhaust ports are designed for where the engine will spend the majority of its operating time. Snowmobiles, due to the variable speed transmission typically spend most of their time at very high rpm values. At these high rpm values, the piston is moving so fast that the exhaust port can be visualized as being open all of the time. The designers then try and prevent the loss of air/fuel mixture exiting the exhaust port by tuning the exhaust to return pressure waves, forcing the air/fuel mixture back inside the cylinder, at this high rpm value. In order to have pressure wave find the exhaust port open, the designers place it so that it opens relatively soon in the pistons motion and stays open for a long period.

The engine exhaust ports, in the as-received condition, remained open for 202 degrees of the crankshaft rotation. By moving the relative position of the exhaust port down 1mm, the exhaust port opens later and closes sooner, resulting in a reduction in the number of degrees of crankshaft rotation the port is open, from 202 to 199 degrees. This seems like a minor change, but it does have the effect of improving the performance of the engine at lower rpms where the tuned exhaust will not be as effective [7].

Tuning the Carburetors

Carburetors accomplish the task of metering and mixing the fuel into an air-stream so that a mixture of air and fuel enters the cylinders. There are two carburetors on the engine, one for each cylinder. Proper adjustment of the carburetors is important to the optimum performance of the engine. Too much fuel in the air/fuel mixture (rich condition) can cause sputtering, heavy exhaust smoke contributing to high emissions levels, and plug fouling. Too little fuel in the air/fuel mixture (lean condition) can cause more serious problems. A severely lean engine will not run because there is not enough fuel to combust, and a slightly less lean mixture results in a rapid increase in engine temperature, fluctuation in engine speed, backfiring (detonation), and possible seizure of the piston to the cylinder walls.

Controlling the amount of fuel introduced into the air stream is accomplished using several methods. A pilot jet meters fuel into the air stream at idle and low speed conditions. A pilot air screw enables the adjustment of the pilot jet air supply by varying the cross sectional area of the air passage, this also has the most effect at idle and low speeds but can be used to fine tune the air/fuel ratio throughout the entire operating range.

The main carburetor system controls the introduction of fuel from 3/8 to full throttle. The main system includes a needle and corresponding needle jet and the main jet. The needle resting position can be changed in order to reduce or increase the amount of metered fuel. The needle can also be replaced with needles of various sizes and taper angles. The main jet can be easily replaced, a larger jet diameter providing more fuel.

Changes in altitude and temperature affect the air density. This affects the amount of air available for combustion. At low elevations and low temperatures, the air has more oxygen per unit volume. Typically most snowmobiles leave the factory calibrated for an altitude of 0-3000ft and ambient air temperatures between –20° to +10°F [9]. If the engine is operated outside these conditions, then carburetor modifications are required to allow a proper ratio of fuel to air (oxygen) to enter the cylinder.

The engine was first tuned on the dynamometer setup. A lambda sensor enabled the team to monitor the air/fuel ratio in the exhaust throughout the operating range. Real-time adjustments were completed so that a relatively lean condition (air/fuel ratio of 15:1) would be present at low speeds, getting richer with engine speed until a relatively rich condition (air/fuel ratio of 12.5:1) is present at full throttle [7]. A ratio of 12.5:1 provides the most power and helps keep the engine temperature at safe levels. During the competition, the emissions testing is conducted at low speeds [1]. By increasing the introduction of fuel at high rpm values in the full throttle range, as would be the case in the acceleration and hill climb events, the maximum power can be developed without fear of engine damage.

The competition takes place at an altitude of 6000-7000ft. The service manual was consulted and the recommended changes to the carburetor were considered when selecting the team's modifications to the carburetor. Due to the engine modifications, carburetor jetting changes were required outside the manufacturer specifications. Team Eco-Snow therefore used the service manual as a reference, and selected carburetor settings appropriate for the modifications made and the altitude at the competition. Minor adjustments were then completed upon arrival in Jackson, Wyoming.

EMISSION CONTROL AND EXHAUST DESIGN

The competition rules [1] state that in order to obtain the maximum of 250 points (representing a quarter of the total awarded points) in the emissions event, the CO levels must be reduced to less than 18 500ppm and HC levels to less than 500ppm propane. This represents a minimum reduction of 97.6% in HC and 82% in CO.

An attempt was made to limit the production of emissions through a series of tuning decisions and engine modifications as described earlier in the report. The selection of a fuel and oil are also important considerations that strongly affect the emission levels. The remaining emissions are then treated with a well-designed exhaust system.

The following three sections detail Team Eco-Snow's selection of fuel and two-stroke oil, as well as the design of the exhaust system.

Fuel Selection

In addition to physical modifications, the choice of fuels and lubricants played an important role in determining the performance and emission levels of the snowmobile. The rules of the competition limited the team's fuel selection to a choice of regular gasoline or gasoline with the addition of 10% ethanol [1]. Through some preliminary testing of the original fan-cooled engine emission improvements were seen when using the 10% ethanol blend (see Figure 2). Team Eco-Snow therefore decided to select this blend as their fuel of choice during the competition.

Oil Selection

There were no restrictions as to the type of oil selected for use in the competition, as long as the oil was commercially available.

Two-stroke snowmobile engines typically inject oil into the flow of air moving through the carburetor. The purpose of the oil is to provide lubrication of the crankcase and the pistons. Many two-stroke oils have been developed over the years and there is an extensive selection with varying available properties. The team examined a number of available oils and decided to complete some tests in order to examine the variation in emitted particulate matter, hydrocarbon (HC) and carbon monoxide (CO) emission levels and exhaust gas temperature. The team selected Blue Marble Oil as it provided the best combination of the stated criteria.

Exhaust Tuning

The exhaust systems of typical two-stoke snowmobile engines are tuned in order to take advantage of the energy of the high-speed exhaust gases. A tuned exhaust system consists of several different lengths of pipe, some cone shaped and others straight, of various diameters. The main sections consist of a diffusing cone and a converging cone. These sections contribute to the engine performance in two ways. First, the diverging cone creates a suction pulse, as the high-speed gas passes thought it, which helps the evacuation of the cylinder of burned gases during the scavenging process. The converging cone reflects a positive pressure pulse that also travels to the exhaust port preventing the escape of fresh air/fuel that is entering the cylinder through the transfer ports. The timing of these events depends on the length of the pipe sections and the temperature of the exhaust gases. The tuned exhaust system is designed to maximize these effects at a particular engine speed, where optimum maximum power is desired [6].

Catalytic Converter

Team Eco-Snow investigated the feasibility of incorporating a catalytic converter in to the exhaust system as a means of reducing the emissions of unburned hydrocarbons and carbon monoxide. Catalytic converters have been used in the exhaust systems of four-stroke engines for years, but are not typically found in two-stroke engines.

Studies have shown that the use of a two-way oxidizing catalytic converter is effective in two-stroke applications, giving reductions in HC and CO of 93% and 84% respectively. After these tests, the catalysts were found to be still structurally intact and free from oil. Studies of three way catalysts were also examined, however, the idea was dismissed. Studies showed that the use of three-way catalytic converters yielded negative results, as they became clogged after a short amount of running time [10].

Type and Size of Catalysts

In one recent study, nine different two-way catalysts were tested and the results were compared [11]. The precious metals used were Platinum (Pt) and Rhodium (Rh) loaded on a honeycomb-style support structure. Different parameters were varied among the groups of catalysts such as diameter, length, precious metal ratio, precious metal loading, and cell density. All catalysts performed well, having HC conversion rates above 80% at an exhaust gas temperature of 600 °C. Higher exhaust gas temperatures yielded conversion rates close to 100%. These results were achieved by running a lean carburetor set-up that provided the catalysts with excess oxygen to help in the conversion reaction [11]. The same result could be achieved by supplying the catalysts with air from an outside source [10].

The results of this study [11] showed the effect of varying certain parameters while others remained fixed. The trends suggest that an increase in diameter, length, or cell density, which in turn provides more surface area for the catalyst material, result in higher levels of HC conversion. Although increased cell density increases HC conversion, it has a negative effect on power since it constricts the flow to the point where the exhaust gas pressure can not drop sufficiently before the next cycle.

The key is to size a catalyst that can sufficiently convert HC and CO without being too large or constrictive to the gas flow. Oversized catalysts are not desired since they waste expensive precious metals that take longer to heat, and give no added benefit. An optimal catalyst size and type was determined along with consideration of location (explained in the next section). The final catalyst specifications are summarized in Table 4.

Type	**Two-way, Monolithic**
Support Structure	Honeycomb
Diameter x Length	4” x 3.5”
Precious Metal Ratio	7:1 (Pt:Rh)
Precious Metal Loading	60 g/ft^3
Cell Density	100 cells/in^2

Table 4: Catalyst Specifications

Catalyst Location

The location of the catalyst is critical for the tuned exhaust system since it must hinder very little restriction on the pressure waves that travel through it. A configuration exists, as suggested by Laimbock [12], that has been shown to dramatically reduce emissions while minimally affecting peak power. The method involves placing the canned catalyst just before the converging cone section of the tuned exhaust. In addition, a pre-catalyst, which is simply a coating of catalyst material on the inside of a section of the diverging cone, is added to take advantage of higher exhaust temperatures experienced closer to the engine. With this set-up, Laimbock [12] tested for emission reductions on a 125cc high-performance motorcycle. After tuning the engine as much as possible for low emissions, by introducing a catalyst system as described above, HC emissions were reduced from 10.4 g/km to 1.9 g/km, and CO emissions were reduced from 1.7 g/km to 0.9g/km [12].

This same approach was adopted by Team Eco-Snow with a modification in the pre-catalyst section. The pre-catalyst coating, as mentioned, would typically be applied with a plasma arc. Since Team Eco-Snow started with a fully assembled exhaust, a procedure to apply this pre-catalyst coating could not be developed in the available time frame. A hot tube was used instead. The hot tube is simply a round, perforated tube containing platinum and rhodium at a ratio of 1:1 with a metal loading of 5g/m^2. The tube is 35mm in diameter and 175mm in length.

The overall configuration employed by Team Eco-Snow is illustrated in Figure 8.

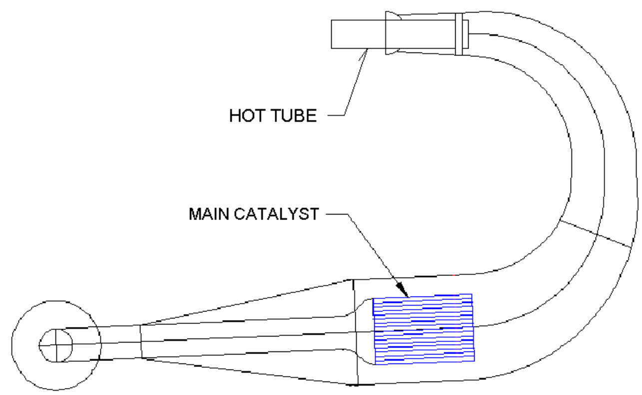

Figure 8: Predicted Attenuation for Diffusing Silencer

Testing the snowmobile after the exhaust was installed resulted in a significant loss of power. This was attributed to the restriction of the airflow of the pre-catalyst hot tube. All of the exhaust flow was forced through the 35mm (inner diameter) opening of the hot tube, whereas the previous inner diameter of the exhaust was 50mm.

Following this observed power loss, the hot tube was removed and the snowmobile was retested. Slightly negative effects on the emission reductions were observed. As well, the speed with which the main catalyst reached an optimum operating temperature was also reduced. However, the loss of power as a result of the hot tube was too substantial and the hot tube was not reinstalled.

NOISE

The competition rules state that snowmobiles must be quieter (at least) than 74 dB measured on the A-weighted scale, 50 feet from the road [1]. Team Eco-Snow investigated the sources of sound that emanate from a typical snowmobile and found that there were several major sources.

The exhaust system is the first major contributor. Present day two-stroke engines come standard with mufflers that attempt to reduce the noise from this source. Other systems such as the intake system and the induction pressure pulses it creates are also almost equally responsible for the total noise. Reducing these sources of sound are achieved through the use of an air-box and insulating material on the inside of the snowmobile body. Team Eco-Snow designed an improved muffler and added more sound insulation, while remaining with a standard air-box design.

Muffler

Silencing or muffling a tuned exhaust system can be achieved without affecting the pressure waves set up by the tuned exhaust system. This is realized by placing the silencing devices after the small exit pipe of the expansion chamber [6].

There are several silencer design alternatives that effectively eliminate noise intensity at different frequencies. All are simple in construction and can be designed using empirical methods once it is known exactly what frequency bands are to be silenced. The most common types of silencers are as follows:

1. Absorption Type. This type of silencer consists of a chamber that has a single pipe running through it. Several holes are drilled into the pipe to connect it to the chamber. The chamber is packed with a sound absorbing material such as glass-reinforced fiber or mineral wool. The absorbing type of silencer is effective in attenuating a wide range of sounds with different frequencies, and is especially effective at frequencies above 2000 Hz. It is not so effective at reducing noise at frequencies below 400 Hz [6].

2. Diffusing Type. This type of silencer consists of a chamber that has an inlet pipe and an exit pipe. The pipes extend into the chamber but are not connected to each other within. There are no sound absorbing materials within the chamber. The diffusing type of silencer provides good sound attenuation at frequencies other than what the chamber resonates at, up to a frequency of about 4000 Hz. At this point its effect become negligible [6].

3. Side-Resonant Type. This type of silencer is similar in design to the absorption type silencer with the exception that there is no sound absorbing material and fewer holes drilled in the pipe wall. The side-resonant type of silencer is extremely effective in silencing noise at the specific frequency at which the chamber resonates. Theoretically, the sound attenuation is infinite there. There is also good silencing capability at adjacent frequencies.

Team Eco-Snow developed a silencer utilizing all three types of silencers described above. The design for the silencer was constrained by the allowable space in the engine compartment. The maximum allowable outside dimensions for the complete silencer was determined. Within those dimensions space for each section of the silencer was allocated based on the attenuation characteristics predicted by corresponding silencer equations. The attenuation of the diffusing and side-resonant sections were maximized by varying independent parameters such as re-entrant lengths, hole size, and number of holes in the predicting equations. The predicted maximized attenuation for the diffusing and side-resonant silencer sections is illustrated in Figure 9 and Figure 10 respectively.

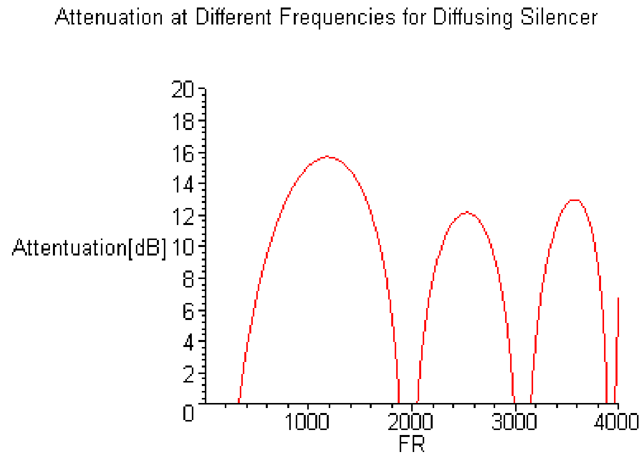

Figure 9: Predicted Attenuation for Diffusing Silencer

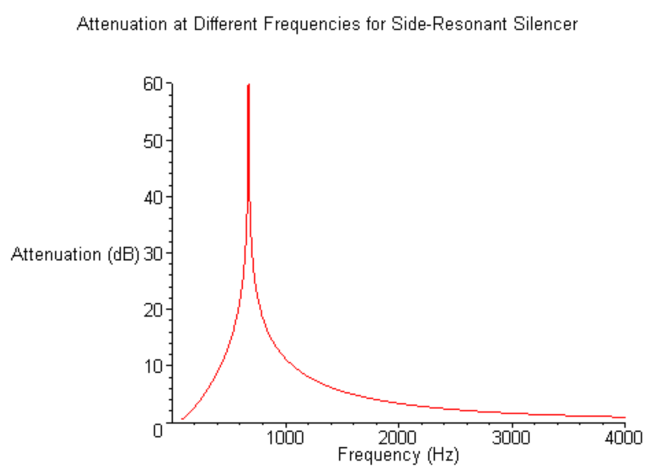

Figure 10: Predicted Attenuation for Side-Resonant Silencer

The silencer, with its three sections, was constructed in two tiers to maximize the length of each section. The final design of the silencer is illustrated in Figure 11.

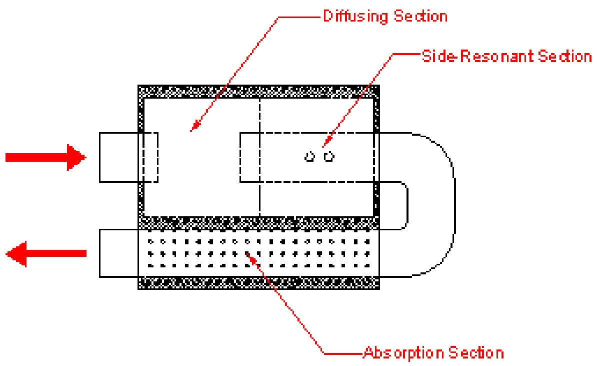

Figure 11: Final Silencer Design

FUEL ECONOMY

The fuel economy event accounts for 100 points of the total points awarded. Team Eco-Snow attempted to minimize the snowmobile's fuel consumption. Many of the engine modifications designed to improve the combustion process also improve fuel economy.

As mentioned earlier in the report, the carburetors can be adjusted to achieve the correct fuel/air ratio. Too much gasoline and the engine will run rich and too little and the engine will run lean. Team Eco-Snow adjusted the carburetors to result in a slightly lean combustion mode. A lean mode results in fewer emissions and a decrease in the overall fuel consumption.

Additionally, all of the bearings and moving parts on the track and the gearbox were examined for wear and damaged parts were replaced. Comparing the developed horsepower from the track of the as-received snowmobile against the output directly from the engine indicated that almost 50% of the power developed by the engine was lost [3]. By reducing frictional losses wherever possible Team Eco-Snow was able to increase the transmitted power. Reductions in frictional losses result in increased efficiency and less consumed fuel.

COST/DURABILITY

The modified snowmobile is expected to be cost-effective; so that snowmobile outfitters can afford to purchase them and still make a profit running tours in national parks [1]. Team Eco-Snow shared this objective. It was the team's responsibility to raise the monies needed to fund the modifications to the snowmobile. Table 5 below contains estimates for the cost of the major conversions. Some of the costs incurred by the team such as the purchase of a liquid-cooled engine are not included in the table. It is assumed that snowmobile outfitters adopting a design similar to that presented in this report would begin with a snowmobile containing a liquid-cooled engine.

Item or Service	Estimated Cost
Standard Exhaust with the addition of catalytic converters.	$750
Muffler/Silencer (Material and Machining Costs)	$150
Engine Modifications (Materials and Services)	$1000
Miscellaneous Material Costs	$200
Total Estimated Cost	**$2100** (Canadian Dollars)

Table 5: Estimate of Cost for Snowmobile Conversion

In order to obtain a successful entry Team Eco-Snow focused on simple concrete solutions. All of the modifications completed to the snowmobile were done with the intention of providing a solution that could be applied to all snowmobiles, and are not restrictive to the competition application.

The costs presented in Table 5 do not include the research and development costs associated with the project. Team Eco-Snow approximate actual costs were $7000.00 CAN over the course of the project. This cost includes equipment, tools, travel, parts and phone costs.

CONCLUSIONS

Team Eco-Snow's first of three objectives is to engineer a snowmobile that exceeds the minimum emissions and noise requirements. The purchase of a liquid-cooled engine provides immediate HC and CO emission benefits over the original fan-cooled engine. In addition, a liquid-cooled engine also enables carburetors to be tuned to a leaner air/fuel mixture, without overheating, resulting in further emission improvements. Modifications to the engine improved the combustion process and the engine operation, and reducing both the consumed fuel and the resulting emissions. A blend of regular gasoline and 10% ethanol also provides significant reductions in engine emissions.

The second objective was to engineer a snowmobile that at least maintains original engine characteristics. Again the purchased liquid-cooled engine provided almost twice the horsepower of its fan-cooled counterpart without any modifications. However, as mentioned previously, modifications provided an improved combustion process. The intention of these actions was to reduce emissions, but has the dual effect of increasing the delivered power from the engine.

The third and final objective is to win the competition, unfortunately Team Eco-Snow had to settle for a second place finish.

RESULTS

Team Eco-Snow completed the CSC2000 with an overall second place finish, receiving a total of two hundred and sixty four awarded points out of a possible one thousand.

The team scored fifty points in the emissions event achieving a 50% reduction on C0 levels and a 95% reduction in HC levels. The averages of the actual emission levels were 54,481ppm CO and 1,058ppm propane HC. These results indicate that the engine modifications and exhaust design were successful, but could be improved in future competitions so as to achieve the maximum 250 awarded points.

Team Eco-Snow placed first in the acceleration run completing the 500ft run in 7.241 seconds. This indicates that the engine modifications were in fact beneficial to the performance of the snowmobile in the high altitude conditions.

The noise event was not successful. Team Eco-Snow's highest recorded noise level as measured during the acceleration run was 78.3 dBA. This did not meet the minimum requirement of 74 dBA and the team was therefore awarded negative one hundred points. This result surprised the team and speculations have been made that the snowmobile had spikes in the low frequency noise band, causing the overall measured noise (as measured with the 'A' scale) to be over the maximum allowable level. Noise and their sources will be examined more thoroughly for the CSC2001.

The fuel economy of the snowmobile was improved by almost 30 percent. The modified snowmobile used 5.203 gallons in a 90 mile run, while the control sled used 7.366 gallons. This improvement is attributed to a combination of the improvements to the combustion process and to adjusting the carburetors to a relatively lean condition.

Team Eco-Snow received zero points during the hill-climb, as did all the other competitors with the exception of one university. Since the modified snowmobile was intended as a trail snowmobile, the suspension and track were not designed to climb a hill having a 60% grade. For future competitions, however, an improved track with larger paddles providing more traction will be considered.

Team Eco-Snow received thirty two out of a possible fifty points for the handling event, thirty eight out of fifty points for the static display, sixty six points of a hundred for the oral presentation, and eighty four points of a hundred in the design report.

RECOMMENDATIONS

Design strategy improvements for following years include the implementation of a control unit and a corresponding fuel injection system. A control unit would provide instructions to the injectors for more accurate metering of the fuel added to the air stream entering the engine. A chart within the control unit would detail this instruction set. The amount of fuel could be altered to meet the specific environmental conditions experienced by the machine. Changes in the pressure and temperature could automatically be compensated for through this instruction set. Such a development would provide emission and mileage improvements above what could be obtained though the continued use of carburetors.

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- Blue Marble Oil
- Polaris Industries
- Walker Manufacturing
- Budd Canada
- Spaneur Incorporated
- MBRP

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APPENDIX

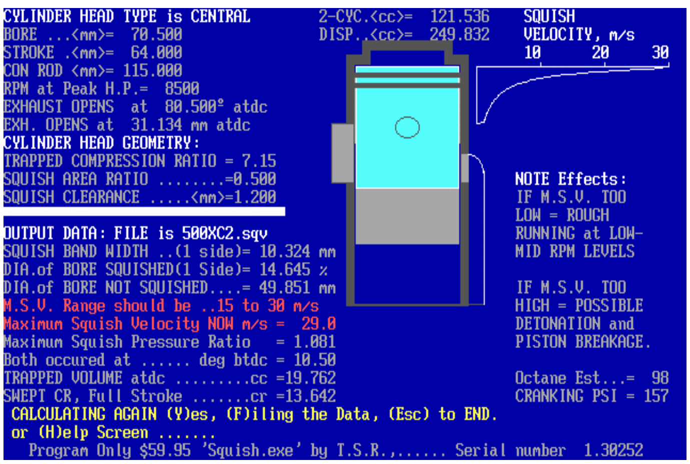

Figure A-1: Unmodified Engine Values Calculated by Squish.exe [8]